

DEVELOPMENT AND EVALUATION OF AN AIRBORNE SEPARATION ASSURANCE SYSTEM FOR AUTONOMOUS AIRCRAFT OPERATIONS

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Abstract

NASA Langley Research Center is developing an Autonomous Operations Planner (AOP) that functions as an Airborne Separation Assurance System for autonomous flight operations. This development effort supports NASA's Distributed Air-Ground Traffic Management (DAG-TM) operational concept, designed to significantly increase capacity of the national airspace system, while maintaining safety. Autonomous aircraft pilots use the AOP to maintain traffic separation from other autonomous aircraft and managed aircraft flying under today's Instrument Flight Rules, while maintaining traffic flow management constraints assigned by Air Traffic Service Providers.

AOP is designed to facilitate eventual implementation through careful modeling of its operational environment, interfaces with other aircraft systems and data links, and conformance with established flight deck conventions and human factors guidelines. AOP uses currently available or anticipated data exchanged over modeled Arinc 429 data buses and an Automatic Dependent Surveillance Broadcast 1090 MHz link. It provides pilots with conflict detection, prevention, and resolution functions and works with the Flight Management System to maintain assigned traffic flow management constraints. The AOP design has been enhanced over the course of several experiments conducted at NASA Langley and is being prepared for an upcoming Joint Air/Ground Simulation with NASA Ames Research Center.

1 Introduction

Despite recent economic and security concerns, demand for air travel is already meeting or exceeding previous levels and is projected to increase further [1-4]. In response to these demands, NASA is investigating a new concept of operations for the National Airspace System, known as Distributed Air Ground Traffic Management (DAG-TM) [5]. DAG-TM has the goal of substantially improving airspace capacity, while maintaining or improving safety. It addresses these goals through a paradigm shift from a centralized, ground-based air traffic management system to a distributed network involving pilots, Air Traffic Service Providers (ATSPs), and aeronautical operational control centers. DAG-TM distributes responsibilities in a way that allows all participants to work within manageable workload levels, while reducing capacity limits and system bottlenecks.

Under DAG-TM, separation assurance responsibilities are assigned to the most appropriate decision maker. Pilots flying appropriately equipped "autonomous" aircraft fly under Autonomous Flight Rules (AFR), where they are allowed to choose their own routes subject to maintaining separation from all other aircraft and conforming to traffic flow management constraints. ATSPs continue to provide separation services to "managed" aircraft unequipped for autonomous operations. Managed aircraft fly under today's Instrument Flight Rules (IFR) and operate in the same airspace as autonomous aircraft. ATSPs also

issue waypoint constraints to all aircraft when needed to meet local traffic flow management needs.

A robust Airborne Separation Assurance System (ASAS) is a key enabling technology for autonomous flight operations under DAG-TM. The Autonomous Operations Planner (AOP) developed at NASA Langley serves as a prototype ASAS that enables pilots to safely self-separate from other aircraft while meeting assigned traffic flow management constraints. It provides a conflict management tool suite consisting of Conflict Detection (CD), Conflict Prevention (CP), and Conflict Resolution (CR) capabilities. These tools are based on needs outlined by RTCA's Airborne Conflict Management (ACM) Committee (RTCA SC186 WG1) [6]. The AOP integrates directly with a research prototype Flight Management System (FMS) to meet assigned waypoint time, speed, and altitude constraints.

Although mature state DAG-TM is a far-term concept, the AOP has been designed to facilitate its eventual implementation onto the flight deck. Any new aviation technology must demonstrate to aircraft owners and operators that it can provide an immediate and significant benefit that substantially outweighs its implementation cost [4]. DAG-TM concept feasibility and benefit studies are addressing the former [7], whereas the AOP design has strived to seriously consider the latter.

AOP design principles account for operator economic issues and global interoperability needs by emphasizing:

- Effective operation using currently available and anticipated information.
- Compatibility with existing aircraft systems and industry standards.
- Pilot participation in a DAG-TM environment under acceptable workload levels.

- Conformance to established flight deck conventions and human factors guidelines.

These design goals are manifested by developing and evaluating AOP in a comprehensive environment consisting of internal and external systems interfaces and human-machine interactions.

2 Modeling the AOP Operational Environment

To meet the design goals described above, a simulated aircraft and airspace environment has been created that places a heavy emphasis on maintaining appropriate levels of compatibility with real-world avionics system architectures. This simulated environment is called the Airspace and Traffic Operations Simulation (ATOS) and resides within the NASA Langley Air Traffic Operations Laboratory (ATOL).

2.1 ATOS

The ATOS is a computer-workstation based airspace simulation that consists of many components, as shown in Figure 1. The components include twelve individual simulated aircraft piloted by a single pilot, multiple pseudo-pilot workstations in which multiple simulated aircraft can be controlled by a single operator, a local air traffic generation tool to provide additional background traffic, and a link to the air traffic control services provided by an offsite facility (the NASA Ames Airspace Operations Laboratory). These components communicate with each other by passing data over TCP/IP using a High Level Architecture (HLA) communications bus.

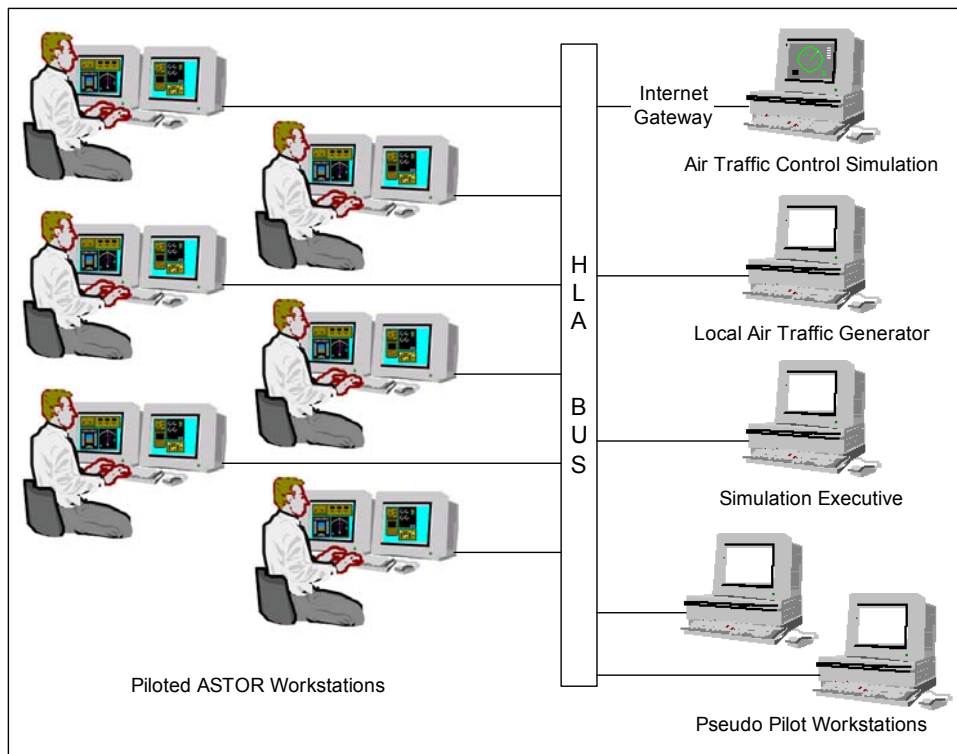


Fig. 1. High-level Structure of the ATOS

2.2 External ASTOR Communications

The data passed over this bus are tightly controlled, in the sense that it is very closely modeled after existing industry standards for the data that would be transmitted via radio signals. For example, aircraft state and trajectory intent data are based on the current version of the Automatic Dependent Surveillance Broadcast (ADS-B) Minimum Aviation System Performance Standards (MASPS) document [8]. Although the DO-242A specification has been extended in certain areas to support the new AOP functionality, great care was taken to maintain the underlying assumptions and limitations inherent in the industry standard. A similar approach has been taken for Flight Information Services Broadcast (FIS-B) data [9].

Traffic data are exchanged between air and ground stations over a modeled data link system that applies a probability of message reception vs. range between the transmitter and receiver. This range model considers message

interference due to other data link messages and interrogations from secondary surveillance radar sites and aircraft Traffic Alert and Collision Avoidance Systems (TCAS).

3 AOP Communications within ASTOR

Each of the piloted aircraft workstations in the ATOS is called an Aircraft Simulation for Traffic Operations Research (ASTOR). Each instantiation of ASTOR represents a commercial transport aircraft, its flight deck systems, and the airborne components of a realistic future Communications, Navigation, and Surveillance (CNS) infrastructure. Current basic aircraft components include: aircraft and engine models; autopilot and autothrottle systems; Flight Management Computer (FMC) and Multi-function Control Display Unit (MCDU); Mode Control Panel (MCP) and Electronic Flight Instrumentation System (EFIS) control panel; EFIS displays such as the Primary Flight Display (PFD), Navigation Display (ND), and Engine Indication and Crew Alerting System display (EICAS); and sensor

systems such as an air data computer, satellite and inertial navigation units, and sensors and controllers associated with aircraft configuration (e.g., flaps, slats, and gear). The flight deck

controls and displays of ASTOR are patterned after the Boeing B-777 airliner. An image of the ASTOR on-screen pilot interface is shown in Figure 2.



Fig. 2. ASTOR Pilot Interface

Advanced technology components of ASTOR include the ADS-B and FIS-B transponders, additions to the ND to support the display of the new ADS-B traffic information, a new traffic display control panel to manage this traffic information, and enhancements to certain FMC functions to support AOP conflict resolutions, such as improved required time-of-arrival (RTA) capabilities and the ability to fly non-idle descent paths.

3.1 ARINC Data Bus Modeling

The internal data flows between components within each ASTOR aircraft are accomplished using a simulated ARINC 429 data bus, which is described below. The specific sources of information provided to the new AOP are then presented within this context.

3.1.1 ARINC 429 Data Bus Model

To provide the desired combination of standards compliance and research flexibility, a new simulated ARINC 429 [10] avionics architecture has been designed and implemented to serve as the inter-process communications backbone of

each ASTOR workstation. This simulated data bus models the equipment labels, channel definitions, and word labels of ARINC 429 without duplicating the physical and electrical signal characteristics of real 429 bus hardware [11]. Each functional module of an ASTOR roughly corresponds to a current-generation avionics component, or to a new research capability that may eventually be incorporated into new or existing flight decks. To support the high data rates of many of these components without resorting to actual 429 bus hardware, a shared memory communications architecture is used. In order to promote the future rapid integration of AOP into flight test vehicles and to develop correct conclusions about the potential of AOP, as well as its associated system requirements, the contents of each channel on the bus remain as close as possible to the definitions described in the 700 series of ARINC characteristic documents (ref. ARINC 702A). As described in the next section, however, some extensions to the standards have been made to support the new research functionality.

3.1.2 Data Bus Extensions to support AOP

New channels have been added to the simulated ARINC 429 data bus to carry the data produced by AOP. These new channels include AOP EFIS Output to carry data for the EFIS displays, AOP FMC Output to carry resolution flight plans to the FMC, and AOP MCDU Output to carry MCDU page data.

In addition to these new AOP bus channels, AOP sometimes requires additional data not previously defined on several existing channels of the ARINC 429 data bus. For example, AOP needs waypoint crossing data (both flight plan requirements and trajectory estimates) for altitude, speed, and time to perform its traffic conflict detection. Therefore, the FMC Trajectory Intent Channel [12] has been extended by defining additional words to

include this information. Although a detailed description of all of these additions and extensions to the simulated ARINC 429 data bus is beyond the scope of this paper, a high-level overview of AOP interfaces to other aircraft systems is presented below.

3.2 AOP Interfaces

To perform its separation assurance functions, AOP communicates with many other simulated onboard aircraft systems. As shown in Figure 3, these other systems include the FMC and MCDU, autopilot and autothrottle, existing EFIS control panel and MCP, air data computer, ADS-B and FIS-B transponders, EFIS displays, and a newly created traffic display control panel.

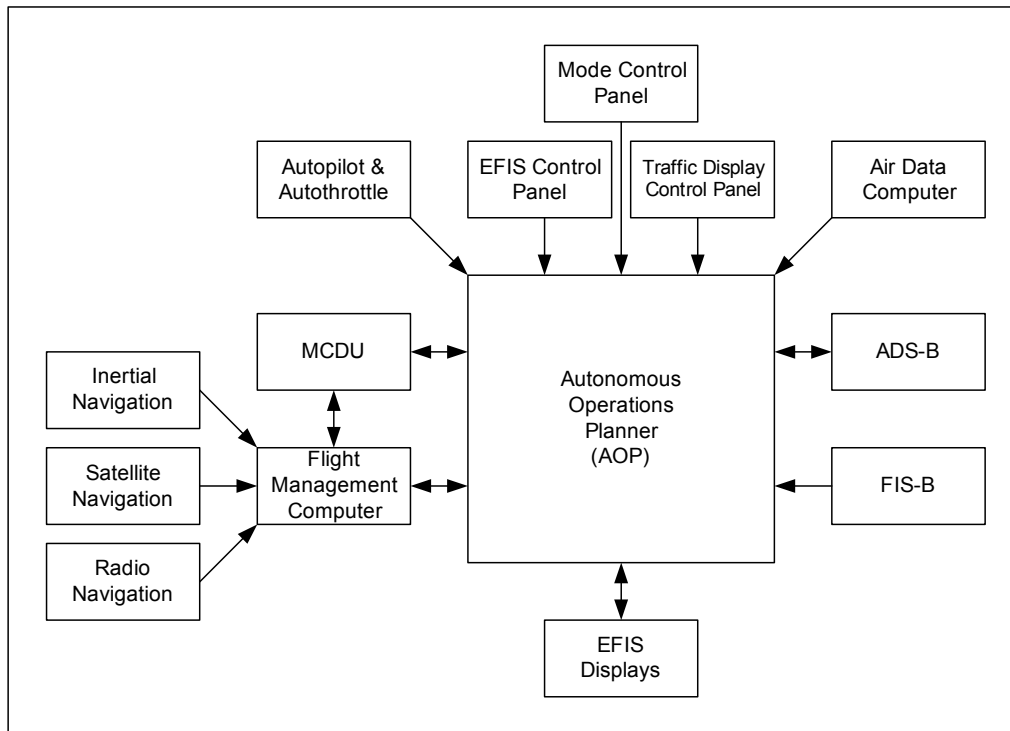


Fig. 3. Overview of AOP System Interfaces

All of these AOP communications with other aircraft systems use the simulated ARINC 429 data bus described above.

3.3 Other Aircraft Sub-systems

Because the focus of this research effort is on DAG-TM, many aircraft systems not related to flight path management, flight guidance, or flight control have not been simulated. For

example, no models of an aircraft electrical system, hydraulic system, or pneumatic system have been included in the ASTOR workstation.

However, for those systems that are required for investigations of new traffic management concepts, a considerable amount of effort has been placed into modeling them as accurately as possible. For example, the lateral and vertical flight guidance modes of the ASTOR autopilot, the FMC functions and MCDU pages, and the EFIS displays and control panels are implemented to be very closely matched to those found on the B-777.

4 AOP Trajectory Processing

Separation assurance applications needed to support autonomous flight operations rely on a comprehensive trajectory processing system within AOP. This system includes the assembly of ownship trajectory information for broadcast over ADS-B and the handling of incoming trajectories received by other aircraft.

Aircraft trajectory information can be grouped into three different categories: state information (position and velocity), target state intent, and trajectory intent. Target state intent includes a singular set of horizontal and vertical guidance targets, such as commanded altitude, commanded heading or ground track, and commanded vertical speed. Trajectory intent includes multiple future target states and is typically in the form of an FMS or Area Navigation (RNAV) flight plan. These categories correspond to typical aircraft control states described below.

Previous research suggests that some amount of intent information provides advantages for ACM applications [13-15]. Many other ASAS development efforts have trajectory processors that handle intent consisting of either some aircraft target states [16-17] or full FMS flight plans [13,18-19].

AOP employs a multi-faceted approach for handling trajectories that processes state information, target state, and trajectory level intent depending on the information available from either the ownship or nearby aircraft. The

AOP trajectory processor has been designed to support a variety of different aircraft types and flying techniques that contribute to intent availability.

4.1 Aircraft Control States

The availability of aircraft intent depends in large part on its operating control state. Control states are affected by autoflight system capability and the choice of horizontal and vertical flight modes selected by the pilot. The three primary control states, referred to here as manual (no flight director), target state, and trajectory are shown in Figure 4. With each successive outer loop, more intent information is available for broadcast and separation assurance applications.

When aircraft are flown manually without use of a flight director, only state (position and velocity) information is available. Under target state control, single commanded states are available in the horizontal and vertical planes (such as roll-out heading or level-off altitude, respectively.) In the outermost loop corresponding to trajectory control, the known aircraft trajectory consists of multiple trajectory change points and connecting flight segments. ADS-B target state and trajectory change messages provide a means for aircraft to exchange the corresponding level of intent with other aircraft and ground stations [8,20].

AOP must adhere to a complex set of trajectory processing requirements due to the multiple control state combinations that may exist between the ownship and nearby traffic aircraft. Most commercial aircraft have several flight modes corresponding to the target state and trajectory control states shown in Figure 4. Flight modes are normally selected through a flight control panel and include choices such as hold current heading, hold current altitude, and maintain track between FMS waypoints. For brevity, the flight control panel is hereafter referred to as the MCP. The pilot can concurrently choose horizontal and vertical flight modes that correspond to different control states, leading to different intent availability in the horizontal and vertical planes.

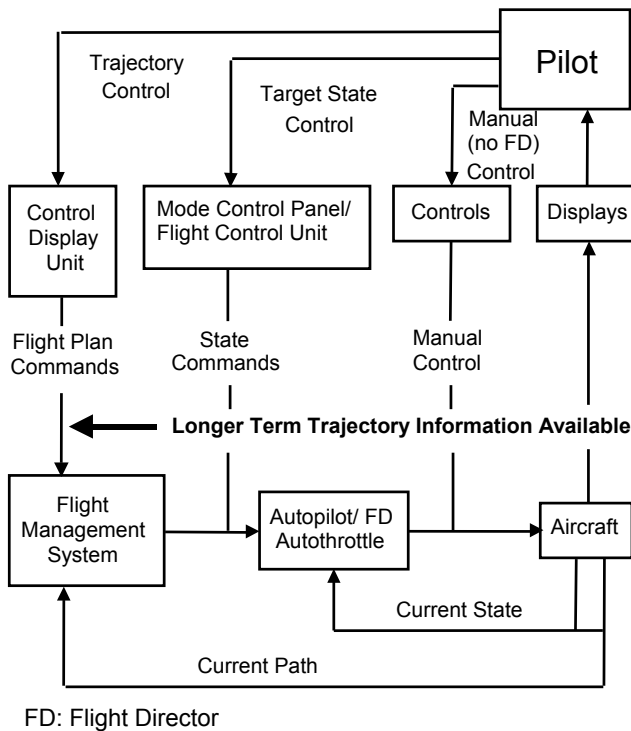


Fig. 4. Aircraft Control States

Typical equipment sets on transport category aircraft (as shown in Figure 4) are capable of providing the associated information to AOP. Other flight hardware may also be able to generate this information. More sophisticated equipment is needed to access outer loop information and may be unavailable on older aircraft. An MCP is the primary interface between the pilot and autopilot when not operating in FMS automated modes. Pilots use the MCP for tactical operations by selecting interim target states such as altitude, heading, vertical speed, and airspeed. The FMS is generally programmed before flight through the keypad-based CDU. A pilot may program an entire route complete with multiple waypoints, speed, altitude, and time restrictions, and desired speeds along different flight segments. Changes may be made to the route description at any time during the flight.

Pilots use the FMS to accomplish strategic goals such as tracking flight progress and flying an efficient route and altitude to the destination. They often leave the programmed flight plan, when trying to meet tactical goals such as

avoiding thunderstorms or resolving near-term traffic conflicts. Under these situations, re-programming the FMS route is often time consuming and impractical. Instead, the pilot may dial a new heading or altitude on the MCP and engage a target state (tactical) flight mode.

Complex paths may be created when an aircraft's trajectory is generated in both MCP and FMS flight modes. Such a situation can occur when the horizontal and vertical modes correspond to different control states or when an autopilot target value interrupts an FMS planned trajectory. The latter case is most common when the MCP selected altitude lies between the aircraft's current altitude and the programmed FMS altitude. In this case, the aircraft will level out at the MCP selected value.

4.2 Command Trajectory

A key feature of the AOP trajectory generator is its ability to create the *command trajectory*. The command trajectory is defined as the path the aircraft will fly if the pilot does not change the automation state or settings used to command aircraft guidance. It considers target states for active horizontal and vertical flight modes and any anticipated mode transitions. Changes to the command trajectory normally result from a pilot input. However, a non-programmed mode transition may also affect the command trajectory, such as reversion to speed priority on descent if the intended vertical path results in an over-speed condition.

To generate the command trajectory, the AOP incorporates autoflight mode logic to determine the combination of active MCP, FMS, or aircraft state targets used to support guidance. These targets may include MCP selected heading or track, selected altitude, selected vertical speed, FMS waypoint predictions, or aircraft state targets. The latter may consist of current heading or current altitude when the aircraft is flying in a Heading Hold or Altitude Hold mode, respectively. The AOP must continually re-evaluate the aircraft state and system settings to ensure that the command trajectory is updated with the latest aircraft guidance and prediction information.

The command trajectory offers benefits for exchanging and processing intent in that it considers multiple flight modes and aircraft target states, rather than relying solely on FMS flight plans. It also incorporates onboard trajectory predictions and uses them instead of programmed autoflight system targets, when appropriate. Reliance on the latter can lead to erroneous trajectory predictions when a pilot action, environmental effect, or performance limitation prevents the aircraft from achieving the programmed target.

For example, a previous pilot-in-the-loop experiment in the ATOL revealed an AOP deficiency in the determination of trajectory change point parameters [21]. To observe the interaction of two subject pilots engaged in a traffic conflict, both aircraft were intentionally assigned the same altitude and time constraints at a common waypoint.

Several pilots conducted avoidance maneuvers that changed the aircraft's actual crossing altitude and arrival time at the waypoint, although the original target values remained resident in the FMS. Example maneuvers included changing the FMS cruise altitude, restricting the FMS descent with the MCP selected altitude, and adding a path stretch that precluded meeting the required time of arrival. The AOP version used at the time continued to broadcast the FMS target parameters as trajectory change points, even though the own aircraft's FMS was predicting it would not meet them. In this experiment, these problems led to inefficiency when one aircraft maneuvered after another had already resolved the conflict. An alternative situation could be envisioned where sending this hazardously misleading information could reduce safety if an aircraft failed to avoid a conflicting aircraft due to its broadcast of erroneous intent.

The command trajectory provides a common definition for all users and helps to address some of these integrity issues. Various organizations have recommended its use for surveillance applications, including the FAA and Eurocontrol during a 2000 Technical Interchange Meeting on shared flight intent [22] and RTCA through its ADS-B MASPS [8].

Although no current aircraft system generates the command trajectory, there are reasons to believe it could be supported with modifications to current systems. Airbus is considering an FMS enhancement that would generate target altitude, a primary component of the command trajectory [23]. Honeywell flight management systems have access to many of the necessary MCP target states and aircraft predicted values over existing data buses [24].

In addition to preparing the command trajectory for broadcasting target state and trajectory change messages, the AOP must interpret these messages from other aircraft. Comparison of ownship and traffic trajectories forms the basis for the conflict detection, prevention, and resolution functions provided by AOP.

5 AOP Traffic Management Functions and Flight Crew Interface

Working with other onboard aircraft systems, the AOP enables pilots to perform the two primary tasks associated with autonomous flight management: self-separation from other traffic and area hazards and conformance with flow management constraints. In addition to accommodating existing standards for aircraft system and data link interfaces, the AOP design emphasizes commonality with established flight crew displays, controls, and procedures.

As indicated in the previous section, AOP must incorporate design approaches to handle a variety of flight mode interactions, while keeping pilots "in the loop" and providing them with effective feedback on conflict situations. The discussion that follows describes the core AOP functions of CD, CP and CR in light of these requirements and indicates how AOP considers these additional tasks in the context of human factors design considerations.

5.1 Conflict Detection (CD)

The CD function provides long-range detection of conflicts between ownship trajectories and hazards, providing flight crews the time to develop and implement optimal

solutions. Any conflicts are ranked and alerted to the crew through visual and aural alerts that conform to the RTCA ACM Group's guidelines on alert levels and implications [6].

The four-dimensional command trajectory is compared with the incoming command trajectories from other traffic and the locations of hazardous weather areas and special use airspace to detect conflicts. It is also compared with time constraints assigned by the ATSP. As discussed above, some combination of state vector, target state intent, and trajectory change intent are presumed to be available over ADS-B, as outlined in the ADS-B MASPS [8]. Intent availability is subject to operating aircraft control state, as discussed above.

Conflict alerting is provided through flight deck displays and interfaces that are based closely on the Boeing 777. Thorough ASAS research conducted at the Berlin University of Technology has presented conflict information on Airbus style displays [18]. Three alert levels (as recommended by the RTCA ACM group) [6] are used to alert the crew to conflicts, with higher levels assigned to proximate and more hazardous situations. The Navigation Display in Figure 5 shows the ownship to be in conflict with another aircraft at co-altitude. A solid amber bar along the current flight path indicates where the ownship is projected to lose and regain the minimum required separation. The AOP currently uses the FAA minimum separation in en route airspace (5 NM or 1000 ft). The conflict aircraft is shown in amber, consistent with the level of threat. When this level of conflict is first detected, the flight crew is also provided with a caution level EICAS message on the multifunction display and a corresponding aural alert. The use of existing displays and industry standards for alert symbology and annunciation should enhance comprehensibility and reduce the amount of necessary crew training.

5.2 Conflict Prevention (CP)

AOP's CP function provides flight crews with guidance for conflict-free maneuvering in common guidance modes. This functionality has

been continuously refined and enhanced following successive human-in-the-loop evaluations of AOP prototypes at NASA Langley [15,21,25]. AOP's CP function has both passive and active elements.

The passive element provides the crew, upon pilot request, with "at-a-glance" information on flight path changes that would cause near-term conflicts. This CP information is presented to the crew by maneuver restriction (no-fly) bands on the ND and PFD as pioneered by the NLR [26]. As an enhancement, AOP's no-fly bands are computed using available intent information from other aircraft. Figure 6 presents an example of the symbology used to depict these no-fly bands on the ND. Assuming the pilot maintains the same vertical command trajectory, a turn within a heading region of 150 through 180 deg will cause a conflict with the other aircraft.

The active element in AOP's CP provides the crew with decision-support on proposed maneuvers, enabled by the crew communicating its intentions to AOP. Since AOP continuously monitors the MCP and CDU, it is aware of any FMS modified (MOD) routes and MCP heading/altitude selections that are yet to be executed. Therefore, when the crew creates any such form of provisional intent, AOP creates 4-D trajectories for that intent and performs CD on the provisional trajectories.

Pilots are alerted to any conflicts detected on these trajectories through the ND, so that they can evaluate the trajectory and make an informed decision on implementing the intended route or target state changes. The alerts used for these provisional maneuvers are shown as dashed loss of separation bars along the provisional flight path. These bars indicate the points of first and last loss of separation if the maneuver were implemented, consistent with conflict detection indications.



Fig. 5. Scenario Showing Conflict at Present Altitude and along FMS Profile Descent

Figure 5 shows a provisional conflict along the current trajectory. The aircraft is flying along an FMS trajectory, prior to its Top of Descent (T/D). The flight crew has not yet dialed down the MCP altitude below the cruise altitude, a necessary pre-condition to enable the FMS descent at the T/D. An AOP provisional trajectory is created based on the crew performing this likely action. The dashed loss of separation region shows that a conflict will occur if the aircraft descends at the T/D. Provisional conflict detection supports the AFR requirement that pilots do not maneuver or change autoflight system settings in a way that causes near-term conflicts with other aircraft.

In the scenario shown in Figure 5, the aircraft's vertical command trajectory is to remain in level flight at the cruise altitude. This level flight trajectory is broadcast to other aircraft. The crew of the aircraft causing the provisional alert is currently unaware of this potential conflict situation. For this reason, AFR pilot training emphasizes the importance of checking for near-term conflicts prior to maneuvering.

5.3 Conflict Resolution (CR)

AOP's CR function provides crews with resolutions in several common aircraft flight modes. They are presented to the crew through existing displays (PFD and ND) and crew interfaces such as the CDU. AOP supports two types of resolutions, referred to as strategic (trajectory-based) and tactical (target state-based).

Strategic resolutions are computed as modifications to the FMS route and displayed as MOD routes on the ND. They provide crews with (a) a solution to the current conflict, (b) a return to the FMS route, (c) protection from creating future conflicts, and (d) conformance to active TFM constraints to the extent possible within ownship performance limitations. The crew is always in full control of the aircraft and its systems, and these resolution advisories are not created or implemented without crew input through the CDU.

Tactical resolutions are presented to the crew as simple "go-to" headings, vertical speeds or altitudes that can be implemented by the flight crew either manually or through the MCP. They are annunciated as simple "bugs" on the ND and PFD. Time-to-conflict considerations determine the extent to which these resolutions protect the ownship from future conflicts. For near-term conflicts, implicit coordination techniques ensure that both aircraft are given compatible resolutions. To perform these coordinated resolutions, the AOP incorporates a modified voltage potential method refined by the NLR [26]. Again, the crew is in full control of the aircraft, and these resolutions can only be implemented by crew input through the MCP.

AOP computes and provides resolutions that match the currently engaged flight modes. If the pilot's horizontal and vertical flight modes correspond to the trajectory control state shown in Figure 6 (FMS guidance) AOP provides a strategic resolution if sufficient time to conflict remains. Otherwise, AOP gives a tactical resolution in the form of proposed target state changes. The green bug in Figure 5 is a tactical resolution suggesting a right turn. These features ensure that AOP is responsive to the

crew's preferences in controlling the airplane [27], and that AOP's resolutions are intuitive and comprehensible to the crew.



Fig. 6. Conflict Scenario Showing Strategic Resolution and Maneuver Restriction Bands

In Figure 6, the pilot has uploaded a strategic resolution into the FMS and it's shown as a MOD route (dashed white line), using Boeing color and symbol conventions. This path resolves the conflict and returns the aircraft to its original flight plan. When the pilot executes this MOD route, the AOP will determine that a conflict no longer exists and will remove the loss of separation bar and no-fly bands.

6 Conclusions

AOP design has been driven by the need for compatibility with external systems, aircraft data sources, and flight deck conventions. It uses information available over modeled data buses and links, based on industry standards. The AOP incorporates a human-centered interface that leverages existing flight crew interface systems. Despite these features, additional work is needed to fully integrate the

AOP into a separation assurance-dependent environment like DAG-TM.

Most of the AOP development to date has focused on longer-term separation assurance rather than near-term collision avoidance. A previous study showed that pilots were able to use the tactical resolution cues to remain a safer distance from pop-up aircraft causing a near term conflict (RB ATM2003 paper). However, AOP design does not currently incorporate the Traffic Alert and Collision Avoidance System (TCAS). TCAS functions as a collision avoidance system and is standard equipment aboard commercial aircraft. An overall consensus exists that TCAS will provide necessary backup protection for separation assurance applications [4]. Considering this approach, the AOP design will need to address a number of important integration issues, including differences in resolution techniques between the tactical resolution system and TCAS resolution advisories and transition to a different source of aircraft state information. TCAS uses its own antennas to determine aircraft range and bearing, instead of ADS-B state vector messages.

The AOP design described here will be evaluated in an upcoming Joint Simulation with NASA Ames Research Center. This experiment will address air/ground coordination issues for DAG-TM and will include both cruise and descent scenarios. AFR and IFR operations will be conducted in the same airspace, modeled after current Dallas Fort Worth sectors. Subject airline pilots at NASA Langley will use the AOP to maintain traffic separation and meet assigned altitude, speed, and time constraints at a terminal area meter fix. Subject controllers at NASA Ames will separate IFR aircraft from each other and assign flow management constraints to AFR aircraft. The experiment should provide a good opportunity to further improve upon the AOP design.

Thorough consideration of aircraft systems and pilot performance issues have led to an AOP design that has contributed to promising results during initial DAG-TM feasibility studies [15,21,25]. Ongoing research and design enhancements will continue to address

detailed integration issues while providing effective decision support for pilots operating in complex DAG-TM environments.

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